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RESEARCH ARTICLE

A Redundancy Based Optimal Placement of Interline Power Flow Controller Using Composite Severity Index for Contingency Management

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Abstract
Contingency assessment is an essential task for the stable and reliable operation of a power system as it predicts the effect of outages in transmission lines and generator units. In this paper, a recurrence of severity based placement strategy for Interline Power Flow Controller (IPFC) has been proposed. Contingency ranking of the lines has been done using Composite Severity Index. A probabilistic based strategy has been adopted for the placement of IPFC. IPFC is placed on the line which has the highest probability of severity during the occurrence for different outages. To verify the proposed methodology, it has been tested on IEEE 14 and 30 bus system. The load on the bus with highest load is further increased gradually up to the critical value and the results have been presented and analyzed to ascertain the effectiveness of IPFC for contingency management.

Keywords
Contingency, Interline Power Flow Controller, Line Utilization Factor, Fast Voltage Stability Index, Composite Severity Index, Optimal Placement

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1 Introduction

Around the world, the instances of blackout or total failure are ever-increasing. Secure operation of power system under both normal and contingency condition has become a very significant problem in today's complex electrical networks. In power system planning, contingency severity calculation is one of the most important aspects of power system reliability.

Several steady state and dynamic contingency ranking methods are used for contingency screening [1-6]. During system disturbances, system stability becomes vulnerable and there is a high risk of moving towards global instability or total collapse or blackout if preventive actions are not taken quickly. FACTS devices are preferred in modern power systems based on the requirement and are found to deliver good solution. Placement of FACTS devices at an appropriate location provides a good solution to blackout prevention [7-12]. Moazzami et al. [13] have presented a new approach for blackout prevention in a power system using parallel FACTS devices along with application of some corrective actions. Several metaheuristic methods have also been adopted for optimal placement of FACTS devices to improve the system conditions post contingency.

Security estimation of a power system under normal and contingency condition is a primary objective of power system engineers. Under contingency condition, voltage instability and line overload become a problem of major concern during operation of power systems. Therefore, in the system contingency ranking, it is necessary to consider voltage stability index along with line overload index for assessing the actual system stress under a contingency. IPFC is the most recent FACTS device, which is highly flexible and versatile. Since, IPFC consists of multiple VSC's with a common DC link, it has the capacity of compensating multiple transmission lines [14,15]. Optimal placement of IPFC for contingency management is an opportunity yet to be explored. Usually FACTS devices are placed on the most severe line to reduce the severity of the line. However, the most severe line may not have a very high probability of occurrence of severity. It is highly probable that some other line in the system may be endangered more frequently at the occurrence of various contingencies. It is assumed that the line with high probability of severity is more in need of a FACTS device for the improvement of the post-contingency condition of the system.

In this paper, an offline long term investment strategy for placement of IPFC is being proposed for protection of power system against contingency. The line which has the highest probability of severity is proposed to be the optimal location for IPFC placement. Two separate indices Line Utilization Factor and Fast Voltage Severity Index have been combined to form a Composite Severity Index (CSI) to evaluate line overloads and bus voltage violations. Line Utilization Factor (LUF) is employed for the measurement of line overloads in terms of both real and reactive power. Fast Voltage Stability Index (FVSI) has been used for voltage contingency ranking. Both indices have been combined to form a Composite Severity Index, which is used to obtain an accurate estimate of overall stress on the line. The IPFC is placed on the line which is repeated most frequently on the severity list of CSI for the various outages. The load on the highest loaded node is increased gradually up to the critical level. The proposed method is implemented and tested on an IEEE 14 and 30 bus system. The results have been presented and analyzed for illustration purposes.

2 Mathematical Model of IPFC

IPFC consists of at least two back to back DC-AC converters connected by a common DC link [16]. V_i, V_j, V_k are complex voltages at bus i, j, k respectively. $V_l = V_l \angle \theta_l (l = i, j, k)$ and V_l, θ_l are the magnitude and angle of V_l. Vse_{in} is the complex controllable, series injected voltage source. It shows the series compensation of the series converter. Vse_{in} is given by $Vse_{in} = Vse_{in} \angle \theta se_{in} (n = j, k)$. Vse_{in} and θse_{in} are the magnitude and angle of Vsein.

The basic model of IPFC consists of three buses i, j and k. Two transmission lines are connected with the bus i in common. The equivalent circuit of the IPFC with two converters is represented in Fig. 1. Z_{sein} is the series transformer impedance. P_{sein} is the active power exchange of each converter via the common DC link. P_i and, Q_i as given in Eqs. (1) and (2) are the sum of the active and reactive power flows leaving the bus i. The IPFC branch active and reactive power flows leaving bus n are P_{ni} and Q_{ni} and the expressions are given in Eqs. (3) and (4). I_{ji}, I_{ki} are the IPFC branch currents of branch j- i and k-i leaving bus j and k, respectively.

$$\begin{aligned} P_i &= V_i^2 g_{ii} - \sum_n V_i V_n \left[g_{in} \cos(\theta_i - \theta_n) + b_{in} \sin(\theta_i - \theta_n) \right] \\ &- \sum_n V_i Vse_{in} \left[g_{in} \cos(\theta_i - \theta se_{in}) - b_{in} \sin(\theta_i - \theta se_{in}) \right] \end{aligned} \tag{1}$$

$$\begin{aligned} Q_i &= -V_i^2 b_{ii} - \sum_{n=j,k} V_i V_n \left[g_{in} \sin(\theta_i - \theta_n) - b_{in} \cos(\theta_i - \theta_n) \right] \\ &- \sum_{n=j,k} V_i Vse_{in} \left[g_{in} \sin(\theta_i - \theta se_{in}) - b_{in} \cos(\theta_i - \theta se_{in}) \right] \end{aligned} \tag{2}$$

$$\begin{aligned} P_{ni} &= V_n^2 g_{nn} - V_i V_n \left[g_{in} \cos(\theta_n - \theta_i) + b_{in} \sin(\theta_n - \theta_i) \right] \\ &+ V_n Vse_{in} \left[g_{in} \sin(\theta_n - \theta se_{in}) - b_{in} \cos(\theta_n - \theta se_{in}) \right] \end{aligned} \tag{3}$$

$$\begin{aligned} Q_{ni} &= -V_n^2 b_{nn} - V_i V_n \left[g_{in} \sin(\theta_n - \theta_i) - b_{in} \cos(\theta_n - \theta_i) \right] \\ &+ V_n Vse_{in} \left[g_{in} \sin(\theta_n - \theta se_{in}) - b_{in} \cos(\theta_n - \theta se_{in}) \right] \end{aligned} \tag{4}$$

Where n = j, k

$$g_{in} + jb_{in} = 1/zse_{in} = yse_{in}, g_{nn} + jb_{nn} = 1/zse_{in} = yse_{in}$$
$$g_{ii} = \sum_{n=j,k} g_{in}, b_{ii} = \sum_{n=j,k} b_{in}$$

Assuming lossless converter, the active power supplied by one converter equals the active power demanded by the other, if there are no underlying storage systems.

$$\mathrm{Re}(Vse_{ij} I_{ji}^* + Vse_{ik} I_{ki}^*) = 0 \tag{5}$$

Where, the superscript * denotes the complex conjugate.

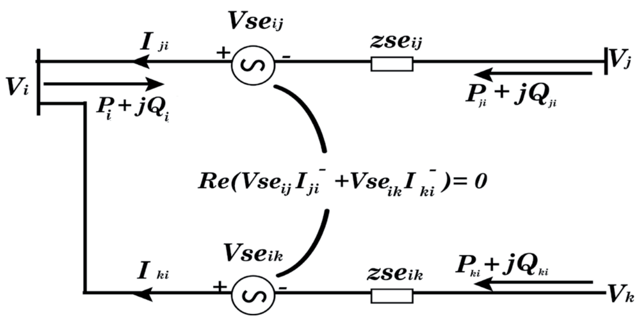

Fig. 1 Equivalent circuit of IPFC

3 Composite Severity Index

3.1 Line Utilization Factor

Line Utilization Factor is an index used for determining the severity of the system loading under normal and contingency condition. It is given by Eq. (6)

$$LUF_{ij} = \frac{MVA_{ij}}{MVA_{ij\,\max}} \tag{6}$$

where, LUF_{ij} is Line utilization factor (LUF) of the line connected to bus i and bus j. $MVA_{ij(max)}$ is Maximum MVA rating of the line between bus i and bus j and MVA_{ij} is actual MVA rating of the line between bus i and bus j .

LUF will be small when the line under consideration carries an apparent within its limits and reaches a high value during overloads. Thus, it provides a precise measure of severity of the line overloads for a given state of the power system. When LUF $\geq$ 1, the line is considered to be overloaded. The overall LUF of the system is the sum of LUF's of all lines and is given by

$$OverallLUF = \sum_{\forall L} LUF \tag{7}$$

Where, L is the no. of lines in the system.

3.2 Fast Voltage Stability Index (FVSI)

Fast Voltage Stability Index (FVSI) is a line-based voltage stability indicator given by Eq. (8)

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \tag{8}$$

where, Z is the line impedance, X is the line reactance, Q_j is the reactive power at bus j and V_i is the voltage magnitude at bus i. FVSI is used to indicate a stable operating region of the load. A line with FVSI value nearer to zero is considered to be a healthy line pertaining to stability. Higher the value of FVSI of a line, weaker is the line with respect to stability, i.e. closer it is considered towards instability. A system is considered to be unstable if FVSI ≥ 1. The overall FVSI of the system is given by

$$OverallFVSI = \sum_{\forall L} FVSI \tag{9}$$

3.3 Composite Severity Index (CSI)

After obtaining the LUF and FVSI values of all the lines for a particular line outage, the composite severity index is calculated as given in Eq. (10)

$$CI_{ij} = w_1 \times LUF_{ij} + w_2 \times FVSI_{ij} \tag{10}$$

where, w_1 and w_2 are the weighting factors of the two indices for line i-j. The sum of w_1 and w_2 is equal to unity. The weighting factors may be used to reflect the relative importance of the indices. In this study, the equal weightage has been given to both the indices. The overall CSI of the system is given by

$$OverallCSI_i = \sum_{\forall L} CSI \tag{11}$$

4 Results and Discussions

4.1 IEEE 14 Bus Test System

An IEEE 14 bus test system has 4 generator buses, 9 load buses and 20 transmission lines as seen in Fig. 2. Bus 1 is the slack bus. Bus number 2, 3, 6, 8 are the generator buses. The remaining buses are load bus. Only load buses have been considered for IPFC placement.

First, the most severe line corresponding to every outage is identified and tabulated down along with the details of the indices values in Table 1, in descending order of CSI. An IPFC with two converters is chosen for the study. Only lines connected between load buses have been considered for IPFC placement.

A pie chart showing the regularity of severity in different lines after the contingency analysis of the system has been presented in Fig. 3. It is observed from the chart that for different outages the line connected between the buses 9-14 is most prone to severity in comparison to other lines. Hence the line 9-14 is chosen for the placement of 1st converter of the IPFC. The Line 9-14 has highest severity when outage of line 13-14 occurs. Hence further analysis is carried out for line 13-14 contingency.

Three lines have been connected with the line 9-14 through a common bus. The CSI values of these lines for line 13-14 outage have been given in Table 2. It is observed that line connected between buses 9-10 has the least CSI value, hence is the healthiest line. Hence the second converter of IPFC is chosen to be placed on line 9-10.Thus further analysis is done for line 13-14 contingency with IPFC placement at 9-14 and 9-10.

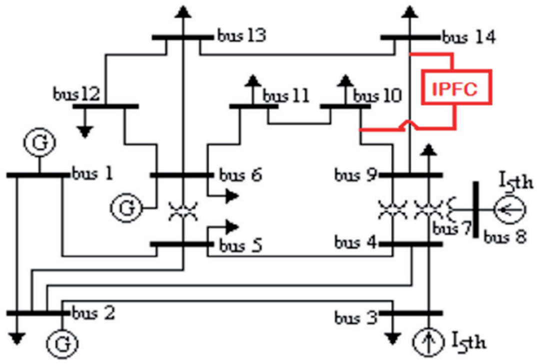

Fig. 2 IEEE 14 Bus Test System with IPFC installed at line connected between buses 9-14 and 9-10

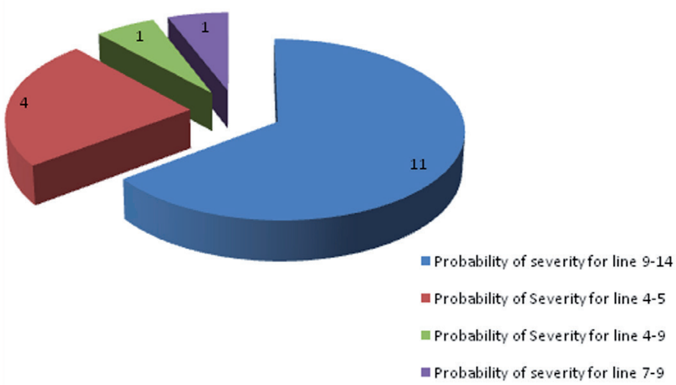

Fig. 3 Probability of Severity of Various Lines for line outages of 14 Bus Test System

Various parameters of the system are studied for three different system conditions - without contingency, with contingency at line 13-14 and with optimal placement of IPFC. The results have been tabulated in Table 3. The parameters taken into consideration are active power loss, reactive power loss, Overall FVSI, Overall CSI, Overall LUF, FVSI, LUF, and CSI of line 9-14. The active and reactive power loss of the healthy system (without contingency) is found to be 22.5451 MW and 82.1714 MVAR respectively. With the outage of line 13-14, it is observed that the active and reactive power loss of the system is increased to 29.2832 MW and 109.3464 MVAR. After placement of IPFC in the line 9-14 and 9-10, the active and reactive power loss of the system reduced to 22.266 MW and 74.518 MVAR respectively. It is observed that contingency in line 13-14 increases the severity of the line 9-14 as given by FVSI and CSI values. Placement of IPFC at the proposed location reduces the value of the indices to pre-contingency state. The overall LUF, FVSI and CSI of the system also improve with placement of IPFC at the proposed location.

Table 1 LUF, FVSI and CSI values of most severe line for various line outage by Contingency Analysis For IEEE 14 Bus Test System

Line Outage		Severe line		LUF (p.u.)	Severe Line		FVSI (p.u.)	Severe line		CSI (p.u.)
FB	TB	FB	TB		FB	TB		FB	TB	
13	14	9	14	0.747	9	14	1.243	9	14	0.9954
1	2	4	5	1.399	9	14	0.513	4	5	0.7398
7	9	4	5	0.429	13	14	0.736	4	9	0.5675
5	6	4	5	1.064	13	14	0.688	4	5	0.5429
2	3	4	5	1.007	9	14	0.516	4	5	0.5108
6	12	4	5	0.599	9	14	0.591	9	14	0.4974
2	4	4	5	0.960	9	14	0.513	4	5	0.4953
6	11	7	9	0.654	13	14	0.562	7	9	0.467
12	13	4	5	0.597	9	14	0.551	9	14	0.4645
4	7	4	5	0.480	9	14	0.546	9	14	0.451
4	5	7	9	0.456	9	14	0.536	9	14	0.4391
3	4	4	5	0.519	9	14	0.512	9	14	0.4323
4	9	7	9	0.603	9	14	0.520	9	14	0.431
2	5	7	9	0.484	9	14	0.508	9	14	0.4286
10	11	4	5	0.630	9	14	0.514	9	14	0.4234
9	10	4	5	0.570	9	14	0.501	9	14	0.4219
1	5	7	9	0.481	9	14	0.502	9	14	0.4211

FB- From Bus, TB- To Bus

Table 2 LUF OF Lines Connected to Line 9-14 for 13-14 Contingency

S. No.	From Bus	To Bus	CSI (p.u.)
1.	9	10	0.1104
2.	9	4	0.3481
3.	9	7	0.5264

Table 3 Comparison of results without Contingency, with contingency and with optimal placement Of IPFC at 9-14 and 9-10

Parameter	Values in different system state		
	Without contingency	With Contingency At 13-14	With optimal placement of IPFC
Active Power Loss (MW)	22.5451	29.2832	22.266
Reactive Power Loss (MVAR)	82.1714	109.3464	74.518
LUF of Severe Line (p.u.)	0.3556	0.7479	0.6406
FVSI of Severe Line (p.u.)	0.5162	1.243	0.7539
CSI of Severe Line (p.u.)	0.4359	0.9954	0.6973
Voltage Deviation (p.u.)	0.6961	1.0793	0.6024
Overall LUF (p.u.)	9.2219	10.1456	8.7642
Overall FVSI (p.u.)	3.6661	4.7349	3.0421
Overall CSI (p.u.)	5.9146	7.4403	5.9031

Bus 4 is the highest loaded bus of the system under consideration. Load at bus 4 is further increased gradually up to the critical level (P = 109.8 MW, Q = 87.9 MVAR) and the results have been presented in Table 4. The load flow program did not converge for any further increase in load beyond this limit. A sample of some most congested lines is taken. The CSI values of these lines for different loadings have been tabulated. From Table 4 it is clear that line 9-14 ranks highest in congestion for all different loadings. With placement of IPFC, the congestion in the line gets reduced to a good extent. The CSI values for line 9-14 for different loads for all the three system conditions have been shown graphically in Fig. 4. The voltage profile of the 14 bus system has been given in Fig. 5. It shows a very good improvement in the voltage of the buses with placement of IPFC at the proposed location.

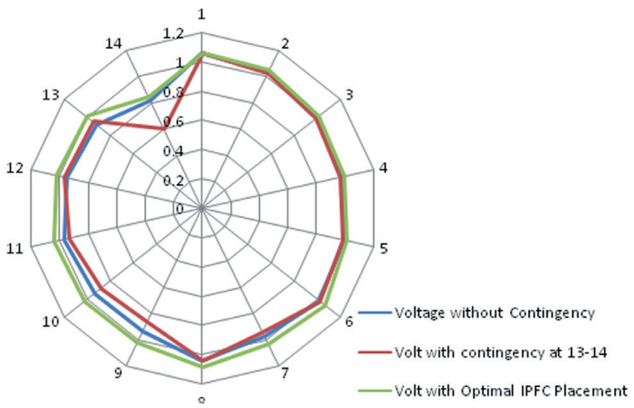

Fig. 5 Comparison of Voltage Profile without contingency, with contingency, and with optimal placement of IPFC under normal loading

Table 4 Indices Of Severe Lines under Increased Loading Conditions

Loading at node 4	Line No	CSI w/t contingency (p.u.)	CSI with Contingency (p.u.)	CSI with Opt. IPFC (p.u.)
P = 47.8 MW Q = 30.9 MVAR (Normal Load)	9-14	0.4359	0.9954	0.6973
	1-5	0.4829	0.5250	0.4393
	4-5	0.3101	0.3525	0.4438
	2-4	0.3590	0.3899	0.3766
	2-3	0.4047	0.4115	0.4110
P = 70.8 MW Q = 60.9 MVAR	9-14	0.4253	1.0710	0.7345
	1-5	0.5706	0.6219	0.5044
	4-5	0.3962	0.4489	0.5139
	2-4	0.4377	0.4792	0.4528
	2-3	0.4468	0.4558	0.4336
P= 109.8 MW Q= 87.9 MVAR (Critical Load)	9-14	0.4124	1.25	0.7689
	1-5	0.7109	0.7632	0.6021
	4-5	0.5161	0.5744	0.6146
	2-4	0.5302	0.6041	0.5555
	2-3	0.4823	0.4973	0.47

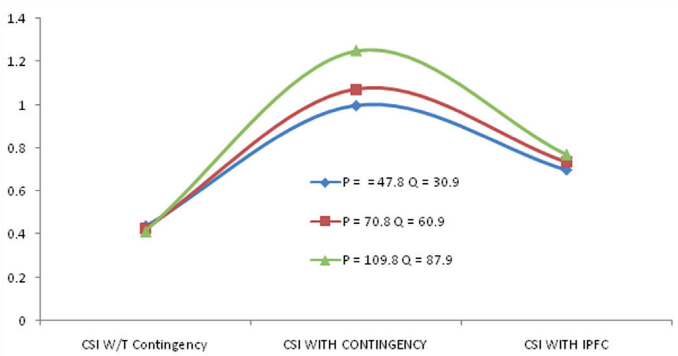

Fig. 4 CSI of line 24-25 at different loads without Contingency, with contingency and with IPFC

4.2 IEEE 30 Bus Test System

An IEEE 30 bus system is considered, in which bus no. 1 is considered as a slack bus and bus nos. 2, 5, 8, 11, 13 are considered as PV buses while all other buses are load bus as shown in Fig. 6. This system has 41 connected lines. The details of the severe lines for each outage with respect to LUF, FVSI and CSI have been given in Table 5, in descending order of CSI. The probability of severity of different lines has been shown in Fig. 7. It is observed that line 9-10 is the most frequently repeated severe line (in terms of CSI) for various contingencies. Hence, line connected between buses 9-10 is chosen for the placement of the 1st converter of IPFC. The maximum value of CSI for line 9-10 is 0.5577 p.u. when there is an outage of line 12-15 from Table 5. Hence, further analysis is carried out for line 12-15 contingency.

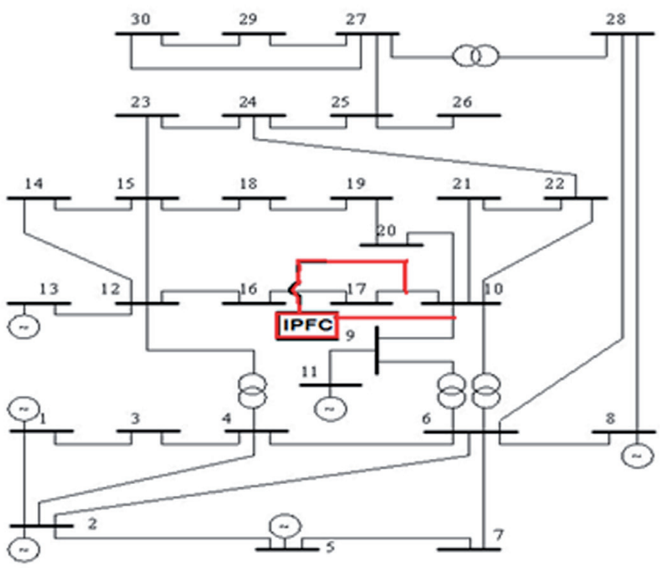

Fig. 6 IEEE 30 Bus Test System with IPFC installed at line connected between buses 9-10 and 10-17

Table 5 LUF, FVSI and CSI values of most severe line for various line outage by Contingency Ranking for IEEE 30 bus Test System

Line Outage		Severe line		LUF (p.u.)	Severe Line		FVSI (p.u.)	Severe line		CSI (p.u.)
FB	TB	FB	TB		FB	TB		FB	TB	
12	15	3	4	0.8477	6	10	0.5438	9	10	0.5577
6	10	3	4	0.8449	28	27	0.4177	9	10	0.5566
6	9	3	4	0.8495	6	10	0.5565	6	10	0.5565
12	16	3	4	0.8417	6	10	0.5115	9	10	0.5323
2	4	3	4	1.0023	6	10	0.4111	3	4	0.5114
15	18	3	4	0.8427	6	10	0.4708	9	10	0.5019
4	6	4	12	0.7072	6	10	0.4215	4	12	0.4938
25	27	3	4	0.8417	6	10	0.45	9	10	0.4872
16	17	3	4	0.8386	6	10	0.4501	9	10	0.486
12	14	3	4	0.8432	6	10	0.4426	9	10	0.4807
15	23	3	4	0.8384	6	10	0.4423	9	10	0.4803
6	28	3	4	0.8431	6	10	0.4288	9	10	0.4757
1	3	9	10	0.6526	6	10	0.4063	9	10	0.4752
3	4	9	10	0.6503	6	10	0.4063	9	10	0.473
24	25	3	4	0.8398	6	10	0.429	9	10	0.4703
18	19	3	4	0.8387	6	10	0.4233	9	10	0.4661
27	30	3	4	0.8444	27	29	0.4884	9	10	0.4648
6	8	3	4	0.8442	6	10	0.4081	9	10	0.4637
14	15	3	4	0.8391	6	10	0.4203	9	10	0.4633
8	28	3	4	0.8397	6	10	0.4165	9	10	0.4627
5	7	3	4	0.8086	6	10	0.4122	9	10	0.4613
29	30	3	4	0.84	6	10	0.4172	9	10	0.4611
23	24	3	4	0.8391	6	10	0.4156	9	10	0.4597
6	7	3	4	0.7573	6	10	0.4232	9	10	0.4577
10	22	3	4	0.8399	28	27	0.4195	9	10	0.4527
22	24	3	4	0.8399	28	27	0.4195	9	10	0.4527
19	20	3	4	0.8418	6	10	0.4047	9	10	0.4509
10	20	3	4	0.85	15	18	0.462	9	10	0.438
10	21	3	4	0.8488	28	27	0.4344	3	4	0.433
10	17	3	4	0.8433	28	27	0.3726	3	4	0.4302
21	23	3	4	0.8396	6	10	0.4026	6	10	0.4026

Line 9-10 is connected to line 6-9, 6-10, 9-11, 10-20, 10-17, 10-21, and 10-22 through a common bus. The CSI values of these lines have been presented in Table 6. It is observed that line 10-17 is the healthiest line in terms of CSI. Therefore, this is the location chosen for the placement of 2nd converter of IPFC. Hence further analysis is carried out for line 12-15 outage and IPFC placement on line 9-10 and 10-17.

Table 6 CSI values of lines connected to line 9-10

S. No.	From Bus	To Bus	CSI (p.u.)
1	6	9	0.2801
2	6	10	0.4125
3	9	11	0.5042
4	10	20	0.2714
5	10	17	0.0343
6	10	21	0.2602
7	10	22	0.0676

The load flow solution was run with IPFC for 30 bus system and the results obtained are given in Table 7. It is observed from Table 7, the active and reactive power loss of the healthy system was 22.288 MW and 102.33 MVAR respectively. With outage of line 12-15 the losses increased to 32.8249 MW and 139.3543 MVAR. When IPFC was placed on line 9-10 and 10-17 the active and reactive power losses reduced to 19.8 MW and 66.823 MVAR. It can also be observed that voltage deviation; overall LUF, FVSI and CSI of the system have been improved to the healthy state (without contingency condition) with the optimal placement of IPFC. The LUF, FVSI, and CSI values of line 9-10 have also been mentioned under the different system conditions, namely, without Contingency, With Contingency at 12-15, with IPFC at 9-10 and 10-17. A reduction in the value of the indices has been observed after the placement of IPFC at the proposed location. CSI of line 9-10 increased from 9.1741 p.u. to 10.9321 p.u. after contingency. When IPFC was placed, the CSI value of line 9-10 reduced to 7.2486 p.u.

Bus 7 is the load bus with the highest load. Loading at node 7 is increased gradually up to the critical level, and the system response as referred to severe lines has been studied and presented in Table 8. The load was increased up to a level P = 299.8 MW and Q = 258.2 MVAR respectively. If any further active or reactive load was added, it was observed that the load flow solution did not converge. Hence, P = 299.8 MW and Q = 258.2 MVAR is the critical load at bus 7. The results show that LUF, FVSI and CSI values of all severe lines have decreased after the placement of IPFC. Out of these lines, line 9-10 is the location for IPFC placement. Figure 8 shows the decrease in severity of line 9-10 with respect to LUF, FVSI and CSI values after the placement of IPFC. The bus voltages of the 30 bus system, under normal loading have been plotted in Fig. 9. It is observed that after the placement of IPFC, the voltage of all the buses have improved and the values are nearly equal to unity.

Table 7 Comparison Without Contingency, With Contingency and With Optimal Placement of IPFC at 9-10 and 10-17 for Normal Loading

Parameter	Without contingency	With Contingency	With Placement of IPFC
Active Power Loss (MW)	22.288	32.8249	19.8
Reactive Power Loss (MVAR)	102.33	139.3543	66.823
Voltage Dev. (p.u.)	3.1435	4.0856	0.9085
LUF of sev. line (p.u.)	0.6385	0.762	0.241
FVSI of sev. Line (p.u.)	0.2922	0.3699	0.0512
CSI of Sev. Line (p.u.)	0.4654	0.5661	0.1460
Overall LUF (p.u.)	12.962	15.1773	11.4397
Overall FVSI (p.u.)	5.3858	4.0856	3.0574
Overall CSI (p.u.)	9.1741	10.9321	7.2486

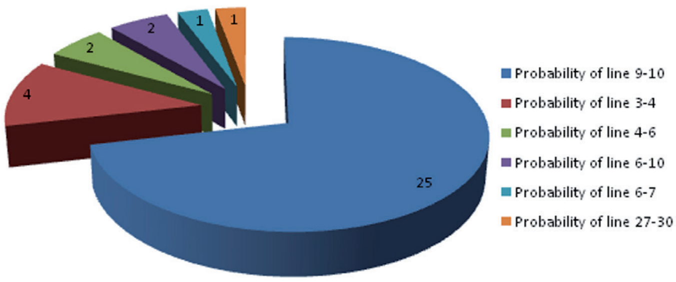

Fig. 7 Probability of Severity of various lines for line outages of 30 Bus Test System

5 Conclusion

IPFC can be very effective in either evading or at least reducing the severity of the system failure to a great extent. Proper placement of the costly device is necessary for its effective utilization.

- An approach for contingency estimation on the basis of probability of severity has been proposed.
- A composite index method has been used for the identification of severity of the system. The composite index is a combination of LUF and FVSI. Hence, CSI has the ability to predict the overall severity of the line. The severe lines for different line outages are identified and ranked in descending order of CSI for both test systems..
- The 1st converter of IPFC is chosen to be placed on the line with highest probability of severity. The 2nd converter is placed on the healthiest line that has a bus in common with the chosen line. It has been established that placement of IPFC effectively reduces line overload,

Table 8 Analysis of some Severe lines with respect to LUF, FVSI and CSI values for increased loading

Loading at node 7	Line No	LUF without contingency (p.u.)	LUF with Contingency (p.u.)	LUF With IPFC (p.u.)	FVSI without contingency (p.u.)	FVSI with Contingency (p.u.)	FVSI with IPFC (p.u.)	CSI without contingency (p.u.)	CSI with Contingency (p.u.)	CSI with IPFC (p.u.)
P = 22.8 MW Q = 10.9 MVAR	9-10	0.636	0.7562	0.2407	0.2849	0.3592	0.0512	0.4604	0.5577	0.146
	3-4	0.8392	0.8477	0.8431	0.0167	0.0164	0.0064	0.4279	0.4321	0.4247
	6-10	0.2342	0.2811	0.1582	0.4165	0.5438	0.2275	0.3253	0.4125	0.1929
	28-27	0.2969	0.3319	0.0871	0.3861	0.448	0.1091	0.3415	0.39	0.0981
	4-6	0.7216	0.7463	0.3905	0.0151	0.0057	0.0696	0.3683	0.376	0.2301
	12-14	0.159	0.3308	0.1342	0.1979	0.3764	0.1624	0.1785	0.3536	0.1483
P = 199.8 MW Q = 158.2 MVAR	9-10	0.6453	0.7818	0.6638	0.3185	0.4097	0.2733	0.4819	0.5957	0.4685
	3-4	1.4868	1.4997	1.5513	0.0043	0.0038	0.0342	0.7456	0.7518	0.7927
	6-10	0.1927	0.2439	0.2249	0.3615	0.5192	0.3138	0.2771	0.3815	0.2693
	28-27	0.286	0.3262	0.2223	0.4192	0.4968	0.3575	0.3526	0.4115	0.2899
	4-6	1.5535	1.5876	0.6475	0.032	0.0211	0.0437	0.7928	0.8044	0.3456
	12-14	0.1669	0.3584	0.3102	0.2148	0.4183	0.408	0.1909	0.3884	0.3591
P = 299.8 MW Q = 258.2 MVAR Critical Load	9-10	0.6602	0.8223	0.5096	0.3645	0.4928	0.1338	0.5124	0.6576	0.3217
	3-4	2.0646	2.1276	2.0021	0.0177	0.0201	0.0688	1.0412	1.0739	1.0354
	6-10	0.1524	0.2042	0.2294	0.2882	0.4936	0.2294	0.2203	0.3489	0.1199
	28-27	0.2784	0.3268	0.1677	0.473	0.59	0.289	0.3757	0.4584	0.2283
	4-6	2.2524	2.347	1.0936	0.0273	0.0117	0.01	1.1398	1.1793	0.5518
	12-14	0.1764	0.3973	0.2582	0.2394	0.4922	0.2582	0.2079	0.4447	0.2981

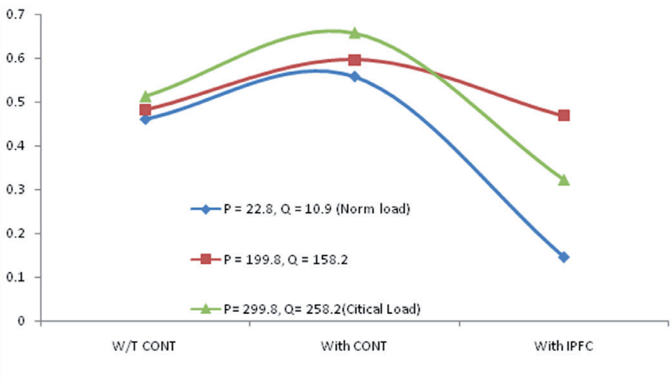

Fig. 8 LUF, FVSI and CSI values for line 3-4 for critical loading without contingency, with contingency and with optimal placement of IPFC

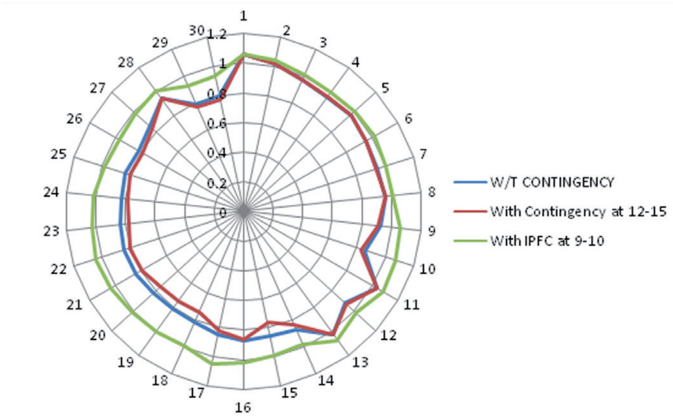

Fig. 9 Voltage Profile without contingency, with contingency and with optimal placement of IPFC

improves voltage stability and reduces the active and reactive power loss of the system. It also reduces the voltage deviation and hence enhances the voltage profile of the system. It has been observed that the voltage deviation, overall LUF, FVSI and CSI of the system are reduced to the pre-contingency level.

- The system loading has been increased gradually to a critical value and the performance of the system has been studied. The IPFC has been found to alleviate the overall performance of the system at all loadings.

References

[1] Amjady, N., Esmaili, M. "Application of a New Sensitivity Analysis Framework for Voltage Contingency Ranking." *IEEE Transactions On Power Systems*. 20 (2). pp. 973-983. 2005. DOI: 10.1109/tpwrs.2005.846088

[2] Donde, V., López, V., Lesieutre, B., Pinar, A., Yang, C., Meza, J. "Severe Multiple Contingency Screening in Electric Power Systems." *IEEE Transactions On Power Systems*. 23 (2). pp. 406-417. 2008. DOI: 10.1109/tpwrs.2008.919243

[3] Wan, H.B., Ekwue, A. O. "Artificial neural network based contingency ranking method for voltage collapse." *Electrical Power and Energy Systems*. 22 (5). pp. 349-354. 2000. DOI: 10.1016/s0142-0615(99)00065-4

[4] Gasperic, S., Mihalic, R. "Analysis of Voltage Stability in Electric Power System with UPFC." *Periodica Polytechnica Electrical Engineering and Computer Science*. 59 (3). pp. 94-98. 2015. DOI: 10.3311/ppee.8604

[5] Krishnan, V., McCalley, J. D. "Contingency assessment under uncertainty for voltage collapse and its application in risk based contingency ranking." *Electrical Power and Energy Systems*. 43 (1). pp. 1025-1033. 2012. DOI: 10.1016/j.ijepes.2012.05.065

[6] Visakha, K., Thukaram, D., Jenkins, L. "Application of UPFC for system security improvement under normal and network contingencies." *Electric Power Systems Research.* 70 (1). pp. 46-55. 2004. DOI: 10.1016/j.epsr.2003.11.011

[7] Jayasankara, V., Kamaraj N., Vanaja, N. "Estimation of voltage stability index for power system employing artificial neural network technique and TCSC placement." *Neurocomputing*. 73 (16-18). pp. 3005-3011. 2010. DOI: 10.1016/j.neucom.2010.07.006

[8] Shaheen, H. I., Rashed, G. I., Cheng, S. J. "Application and comparison of computational intelligence techniques for ptimal location and parameter setting of UPFC." *Engineering Applications of Artificial Intelligence*. 23 (2). pp. 203-216. 2010. DOI: 10.1016/j.engappai.2009.12.002

[9] Shaheen, H. I., Rashed, G. I., Cheng, S. J. "Optimal location and parameter setting of UPFC for enhancing power system security based on Differential Evolution algorithm." *Electrical Power and Energy Systems*. 33 (1). pp. 94-105. 2011. DOI: 10.1016/j.ijepes.2010.06.023

[10] Tiwari, A. "Optimal Allocation of Dynamic VAR Support Using Mixed Integer Dynamic Optimization." *IEEE Transactions On Power Systems*. 26 (1). pp. 305-314. 2011. DOI: 10.1109/tpwrs.2010.2051342

[11] Varshney, S., Srivastava, L., Pandit, M. "Optimal location and sizing of STATCOM for Voltage Security Enhancement using PSO-TVAC." In: *International Conference on Power and Energy Systems*. pp. 1-6. 22-24. Dec. 2011. DOI: 10.1109/icpes.2011.6156646

[12] Lashkar Ara, A., Aghaei, J., Alaleh, M., Barati, H. "Contingency-based optimal placement of Optimal Unified Power Flow Controller (OUPFC) in electrical energy transmission systems. *Scientia Iranica*. 20 (3). pp. 778-785. 2013.

[13] Moazzami, M., Hooshmand, R. A., Khodabakhshian, A., Yazdanpanah, M. "Blackout Prevention in Power System Using Flexible AC Transmission System Devices and Combined Corrective Actions." *Electric Power Components and Systems*. 41 (15). pp. 1433-1455. 2013. DOI: 10.1080/15325008.2013.830655

[14] Ushasurendra, S., Parathasarthy, S. S. "Congestion managerment in deregulated power sector using fuzzy based optimal location for series flexible alternative current transmission system (FACTS) device." *Journal of Electrical and Electronics System Research*. 4 (1). pp. 12- 20. 2012. DOI: 10.5897/jeeer11.143

[15] Ratniyomchai, T., Kulworawanichpong, T. "Evaluation of voltage stability indices by using Monte Carlo simulation." In: *Proceedings of the 4th IASME / WSEAS International Conference on Energy & Environment (EE'09)*. pp. 297-302. 2009.

[16] Zhang, X. P. "Modeling of the interline power flow controller and the generalized unified power flow controller in Newton power flow." *Generation, Transmission and Distribution, IEE Proceedings*. 150 (3). pp. 268-274. 2003. DOI: 10.1049/ip-gtd:20030093